A new test for the characterization of suffusion into embankment and dam

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ICSE6-XXX

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Jacques MONNET[1], Olivier PLE[2], Duc Manh NGUYEN[3], Pierre PLOTTO[4]

[1]UJF-Grenoble 1
UJF-Grenoble 1 , CNRS UMR 5521, 3SR Lab, Grenoble F-38041, France – email : jacques.monnet@ujf-grenoble.fr

[2]UJF-Grenoble 1
UJF-Grenoble 1 , CNRS UMR 5521, 3SR Lab, Grenoble F-38041, France – email : olivier.ple@ujf-grenoble.fr

[3]UJF-Grenoble 1
UJF-Grenoble 1 , CNRS UMR 5521, 3SR Lab, Grenoble F-38041, France – email : duc-manh.nguyen@hmg.inpg.fr

[4]IMSRN
IMSRN, Montbonnot F-38330, France; pierre.plotto@imsrn.com

Internal erosion is the displacement of fine particles of a soil under the action of an internal flow. These mechanisms could be at the origin of damage on embankments and earth dams. Risks are linked to the nature of the floods but also to the construction of the embankments devoid of monitoring system. Then, it is necessary to detect the weak zones at the origin of damage and understand the phenomena of internal erosion. For that, a new experimental device has been carried out in our laboratory. This experiment named "Cross Erosion Test" and calibrated with a numerical simulation consists of the injection, in a first drilling, of clean water and the recovery, in a second drilling, of water charged with particles. In function of the soils and the flow and the initial state of the soils, internal erosion is characterized and particles eroded measured. In this paper we present this new experimental device and preliminary results.

Key words

Internal erosion, in-situ test, numerical calibration

I INTRODUCTION

The internal erosion of soil results from seepage flow. It appears to be the main cause of severe hydraulic failure for dams and dikes. All around the world, the dams which exhibit damage or failure present a risk of internal erosion in 46% of the cases observed [Foster and Fell, 2000]. In France, 70 critical cases have already been detected. When internal erosion is suspected, the delay to failure is hardly predictable. Then, authorities should be able to develop effective emergency action plans to prevent casualties. Previously, it is necessary to understand phenomena of internal erosion. Four types of internal erosion process can be identified: evolution of defects in the soil matrix, regressive erosion, internal suffusion and external suffusion between two soils. This study deals with the description of the suffusion process. Suffusion is an internal erosion process where fine soil particles are displaced by seepage flow through the soil matrix. A state of the art can be found in the literature [Fell and Fry, 2007] and several laboratory studies have been carried out on the subject [Wan and Fell, 2004] but mainly with the development of the Hole Erosion Tests (HET). In this paper, we present a new experimental device named Cross Erosion Test (CET), which is devoted to the measurement of the initiation of the suffusion. The test consists of the injection, in a first drilling, of clear water and the recovery, in another drilling, of water charged with particles. In a first part, this experiment is calibrated with a numerical simulation. In a second part some preliminary experimental results are analysed. Concluding remarks show the possibility to characterize internal erosion into a specific soil. This technique can be transposable, in-situ, to consider risks of internal erosion on dams and dikes.

II DESIGN OF THE CROSS EROSION TEST

The initiation of internal erosion is determined by a critical hydraulic gradient [Arulanandan and Perry, 1983; Den Adel et al., 1988; Khilar et al., 1985; Terzaghi et al., 1996; Vardoulakis and Papamichos, 2001]. But internal erosion has been found in precise conditions of particle size for granular materials, and different granulometric criteria have been proposed [Kenney and Lau, 1985; Terzaghi et al., 1996; Skempton and Brogan, 1994; Monnet, 1998]. All referred authors point out a risk of internal erosion when particles sizes and void opening sizes allow particles movement. This approach involves that the amount of eroded material needs to be quantified, i.e. the amount of washed-out material into the outflow has to be measured. However, problems may appear in case of clogging during the flow of particles displacement [Faure et al., 2006; Lafleur, 1999]. This phenomenon increases the risk of instability.

The principle of the test is control in-situ (inside dams) an hydraulic flow so that the internal erosion should be eventually detected and measured. The test uses (Fig. 1) two boreholes. In the first one, clear water is injected with an imposed water head (h_I) or a chosen volumetric flow (Q_I). In the second one, the water charged with particles is extracted from the soil and analysed. The output water flow (Q_P) is controlled with an electronic pump. Q_P and h_I are measured, which allows to control the hydraulic conditions of internal erosion.

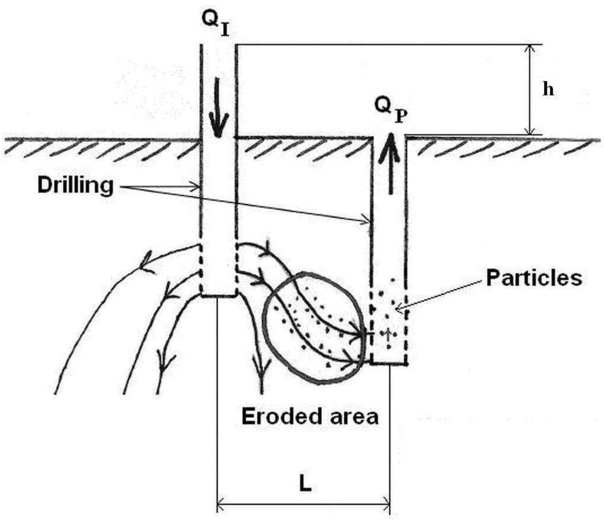

Figure 1: Diagram of the cross erosion test

Figure 2: The tank used with the two boreholes and the pumping system

	k m/s	d_{10} mm	d_{15} mm	d_{50} mm	d_{60} mm	d_{85} mm	C_u
$soil_1$	$6.8.10^{-5}$	0.20	0.25	0.89	1.85	7.91	9
$soil_2$	$8.8.10^{-6}$	0.17	0.22	0.60	0.81	5.79	4

Table 1. Characterisation of the soils tested.

III NUMERICAL STUDY OF THE CROSS EROSION TEST

For the design of the laboratory test a numerical model has been built. This simulation allows checking the limit conditions and the hydraulic gradient. The first numerical model used a Plaxis 2D finite element mesh. As the soil is composed of a mixture of sand and gravel (Table 1), the average permeability (k) is chosen to be k = 4.10^{-5} m/s. The length of the model (0.5 m) is equal to dimension of the tank used (Fig. 2). The height (0.55 m) is equal to the height of the soil into the tank. The water head at the injection (h_I) is equal to 0.20 m. Two conditions have been tested, an unsaturated soil and a saturated one. The field rates of the flow are presented below. For the unsaturated condition (Fig. 3) the water table is located between the injection and the pumping so that the soil around the pumping is unsaturated and then risk of pumping air exists. This phenomenon should affect the results of the test. The situation with a saturated soil (Fig. 4) is safety and the air cannot reach the pumping borehole. This configuration was chosen for the experimentation.

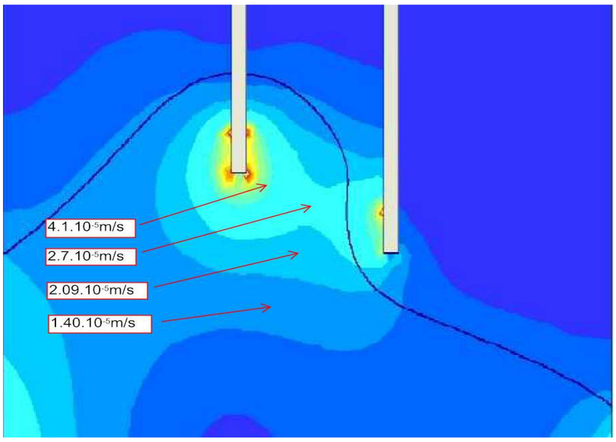

Figure 3: Numerical simulation of the rates of the flow for unsaturated soil

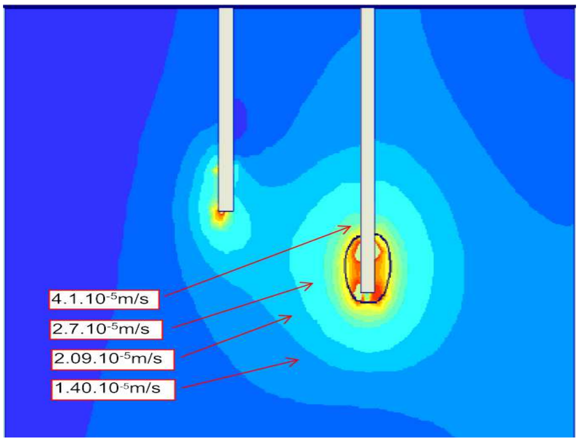

Figure 4: Numerical simulation of the rates of the flow for saturated soil

The second numerical model used a 3D mesh (Fig. 5) with Comsol 3.5 of size (0.55 × 0.50 × 0.40 m). For the same conditions at the injection (0.74 m from the bottom of the tank) and for the same soils, the gradient of water flow, for different water heads at the pumping borehole (h_P), is shown on Fig. 6 to Fig. 10. The permeability of the soil is chosen equal to the measured value (k = $1.4.10^{-5}$ m/s) and the Darcy law (1, 2) is assumed:

$$V_i = -k.\frac{\partial h}{\partial x_i} \quad (1)$$

$$\nabla^2 h = 0 \quad (2)$$

Qualitatively, the maximum gradient of the water flow (light blue) is concentrated around the injection for h_P in the range of -0.1 m to -0.5 m (Figs. 6-7) and concentrated around the pumping borehole for h_P between -2 m and -7 m (Figs.9-10). This study allows us to simulate the pumping effects.

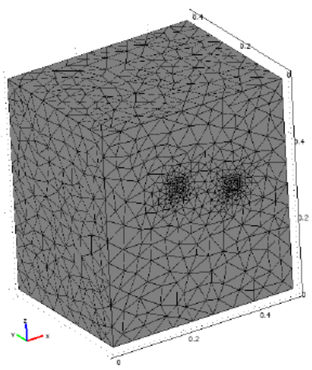

Figure 5: The 3D-mesh (15 661 elements).

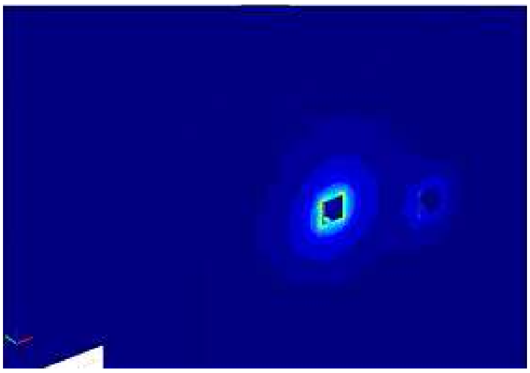

Figure 6: h_P = -0.1 m.

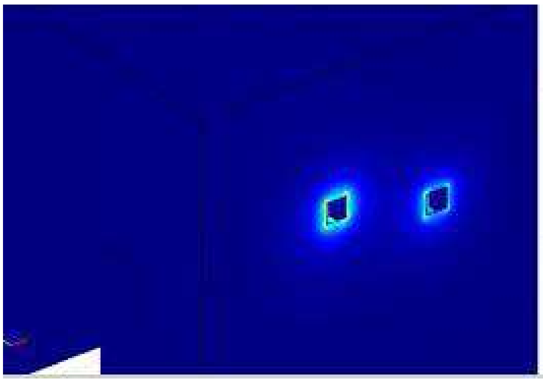

Figure 7: h_P = -0.5 m

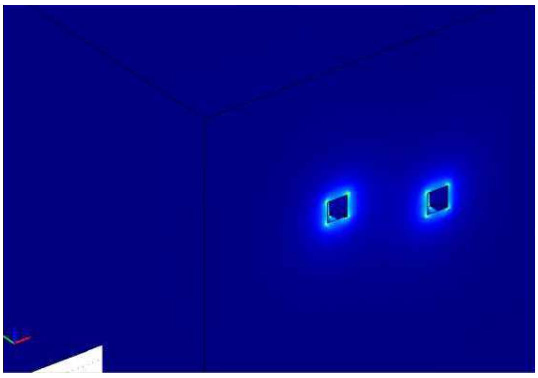

Figure 8: h_P = -0.74 m

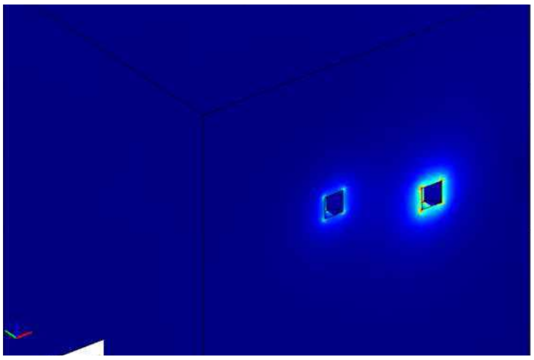

Figure 9: h_P = -2 m

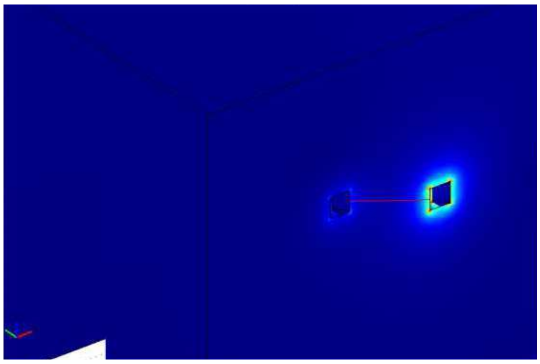

Figure 10: h_P = -7 m

Moreover, the numerical simulation allows the determination of the rate of flow along the shortest trajectory of the water flow. If we study (Fig. 11) the shortest trajectory of the water flow between the injection and the pumping, it can be seen that the speed of the water increases around the two boreholes. Consequently, a uniform value of the water flow cannot be reach. If the water head for the pump (h_P = -0.74 m) is symmetrical from the injection (h_I = 0.74 m) the same speed is obtained around the injection and close to the pump.

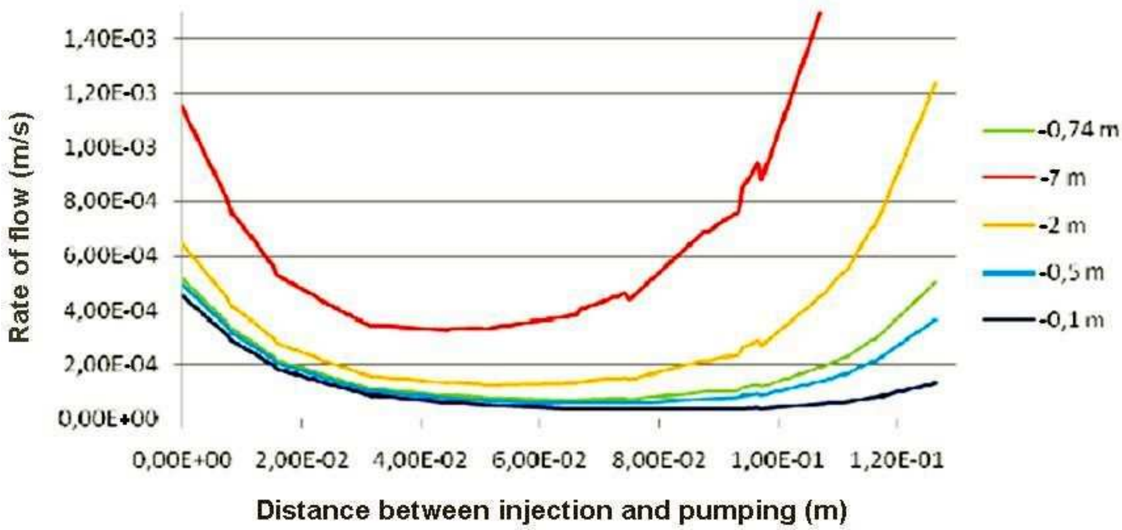

Figure 11: Rate of flow between injection and pumping.

IV EXPERIMENTAL RESULTS

IV.1 Experimental conditions

Two mixtures of soil are studied (Figure 12): the first one (soil1) with 60% of sand (0/2 mm) and 40% of gravel (2/20 mm) and the second one (soil2) with 75% of sand (0/2 mm) and 25% of gravel (2/20 mm). Results are given in Table 1 where d_n represents the diameter of the grain for a cumulative sieved of n% and C_u the coefficient of uniformity.

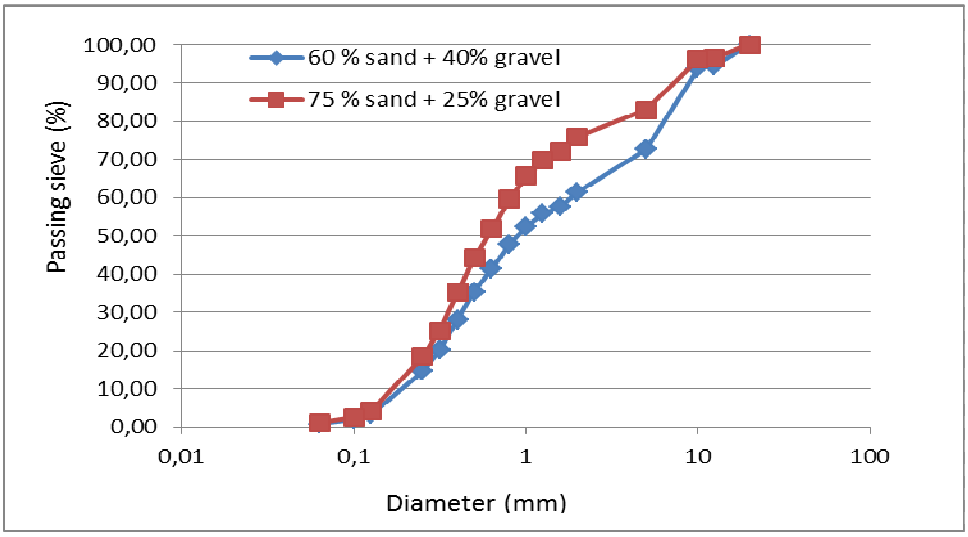

Figure 12: Granulometric curves of Soil1 (60% sand + 40% gravel) and Soil2 (75% sand + 25% gravel)

Filling the tank with soils requires a special attention. Two techniques have been used:

- the tank can be filled by pluviation in air. This technique shows some limits as blocked air bubbles (Fig. 13),
- the tank can be filled under a thin layer of water. The sample seems to be saturated without air bubbles and only small stratification of the soil appears (Fig. 14).

Risk of weak compaction around the pipes remains for the two methods and the water head should be carefully controlled to avoid soil boiling (Fig. 15). The second method was chosen with an over compaction around the pipes.

IV.2 Preliminary results

Only few tests have been carried out.

For the first experiment (soil1), the volumetric flow Q_I is imposed and chosen equal to 0.06 l/mn. For a constant injected hydraulic load (h_I), the pumped water flow Q_P can be controlled by the power of the pump. Parameters are: injected water head h_I fixed to 0.1 m above the soil surface, the power of the pump which can be changed in the range of P (100 W) to 2 × P and the filtration opening size (FOS) of the pump equal to 1.5 mm. Effects are shown below (Fig. 16). When P is maximum (2 × P), the water flow decreases during time (Fig. 16). This indicates a possible clogging and a presence of internal erosion. When the power of the pump decreases (1.5 × P), the water flow (Q_P) is constant and no internal erosion is observed (Fig. 16).

For the second experiment (soil$_1$) parameters are: injected water head h_I fixed to 0.53 m above the soil surface and the power of the pump P equipped with the same filtration opening size (FOS). This power is equivalent to a water head increase of 1,14m, and the loss of water head between injection and pumping can be measured equal to 0.61m. This test allows observing conditions of internal erosion when Q_P decreases during time in the range of 0.21 l/mn to $7.1.10^{-5}$ l/mn (Fig. 17). Preliminary results on particles recovery are also found. During tests, Q_P is recovered and particle weight is measured with the help of a precision balance (± 0.01 g). The evolution of the particle weight along time is shown (Fig. 17). A total weight of 82 g is recovered which correspond to 0.04% of the soil. This first experiment exhibits internal erosion.

As the length of the shortest trajectory is 0.155m, the experimental hydraulic gradient could be found in Table 2 (col.5). In that test, the experimental permeability in Table 2 (col.2) is larger than the

Figure 13: air bubbles after pluviation process

Figure 14: stratification after underwater compaction

Figure 15 : soil boiling close to injection pipe

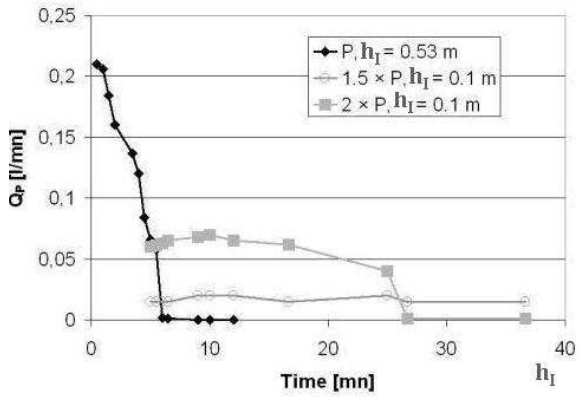

Figure 16: Variation of Q_P in function of the power of the pump

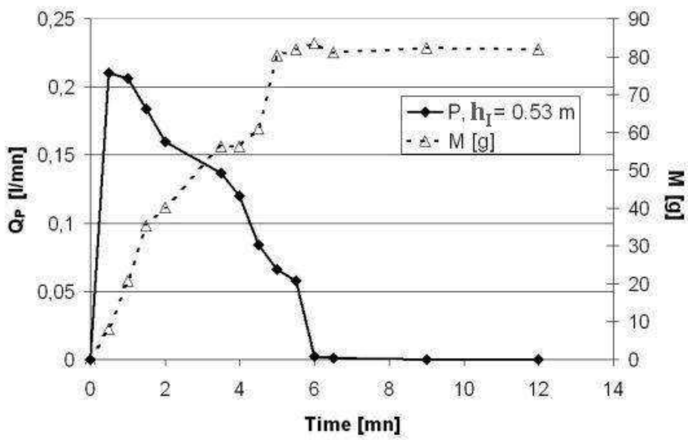

Figure 17 : Variation of Q_P and mass of particles extracted from the soil

theoretical value of the relation (3) [Monnet, 1998]. As a consequence, the hydraulic gradient which insure instability should be larger than (Table 2, col.6) the Terzaghi value (4). This is observed for $soil_1$ which exhibit suffusion:

$$k > 0.01.d_{15}^2 \quad (3)$$

$$i_{exp} \geq i_{Terzaghi} = .\frac{\gamma_s - \gamma_w}{\gamma_w} \quad (4)$$

A second suffusion criterion could be used with the relation (5) [Lafleur, 1999]. In that formula d_I is the diameter of the eroded particle, which depends on the uniformity coefficient C_u. FOS is the diameter of filtration (Table 3, col.2-3). As proposed previously [Lafleur, 1999], the value of d_I (Table 3, col.4) is equal to d_{50} for $C_u > 6$ and equal to d_{85} for $C_u < 6$. The ratio R_r between these values (5) smaller than one, allows to define the hydraulic risk along Lafleur conditions:

$$FOS/d_I < 1 \quad (5)$$

For $C_u > 6$ ($soil_1$) the criterion is not verified and the soil is stable (Table 3). Here a stable soil from Lafleur condition is found to be unstable from experimental and Monnet conditions.
For $C_u < 6$ ($soil_2$), the criterion is verified and suffusion may appear (Table 3).

	$k_{exp.}$ m/s	k_{Monnet} m/s	ρ_{sat} g/cm3	$i_{exp.}$	$i_{Terzaghi}$
$soil_1$	$6.8.10^{-5}$	$6.25.10^{-4}$	2.11	3.9	1.11
$soil_2$	$8.8.10^{-6}$	$4.84.10^{-4}$	2.09	-	1.03

Table 2. Hydraulic gradient [Monnet, 1998]

	FOS mm	C_u	d_I mm	$Rr = FOS/d_I$	Result
$soil_1$	1.5	9.25	0.89	1.68	Stable
$soil_2$	1.5	4.76	5.79	0.26	Suffusion

Table 3. Suffusion criteria [Lafleur, 1999]

V CONCLUSIONS

This paper deals with the process of characterisation of internal erosion with the use of a new laboratory test the Cross Erosion Test.

These few tests show that a soil which is stable from granulometric criteria, may exhibit suffusion for an hydraulic gradient larger than the Terzaghi critical gradient.

This test should be improved by precise measurements of the water head, the pressure flow and the soil mass extracted. This approach should be transposed in-situ for a diagnostic of inner erosion into earth dams and embankments under temporary hydraulic conditions. This first analysis constitutes a preliminary approach to test the sensitivity of the soil to internal erosion. The analysis of the size and the shape of eroded particles should be carried out using a digital images correlation process.

VI ACKNOWLEGMENTS AND THANKS

The authors are grateful for the support of the National Project Erinoh and his director J.J.Fry.

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